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Novel GaN-based vertical heterostructure field effect transistor structures using crystallographic KOH etching and overgrowth

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ABSTRACT

A novel V-groove vertical heterostructure field effect transistor structure is proposed using semi-polar (11-22) GaN. A crystallographic potassium hydroxide self-limiting wet etching technique was developed to enable a damage-free V-groove etching process. An AlGaN/GaN HFET structure was successfully regrown by molecular beam epitaxy on the V-groove surface. A smooth AlGaN/GaN interface was achieved which is an essential requirement for the formation of a high mobility channel.

1. Introduction

Lateral GaN-based heterostructure field effect transistors (HFETs) has attracted much attention for power applications due to the wide band gap (3.4 eV) and the excellent transport properties of the two-dimensional electron gas (2DEG). Devices with voltage blocking capability up to 650 V for power switching applications are commercially available [1] whilst devices with more than 1000 V breakdown voltage (V_{br}) have been experimentally established [2]. However, many issues have arisen at high voltage such as surface-related current collapse, buffer induced dynamic on-resistance and threshold voltage hysteresis. Hence, reliable devices with >1000 V blocking capability will likely require vertical structures. The development of GaN vertical transistors so far are limited to the current aperture vertical electron transistor [3–6], its variations [7–9] and metal-oxide-semiconductor (MOS) structures [10,11] with best reported V_{br} around 1.6 kV. The fabrication of these devices involves dry-etching in the channel region which can cause issues such as leakage and threshold voltage instability. M. Kodama, et. al. [12] proposed a wet etching technique to remove plasma damage in the trench in an MOS structure where an inversion layer is induced by a gate bias. However, MOS inversion structures generally suffer from low electron mobility and hence low transconductance. To address the above mentioned concerns, we propose a novel V-groove vertical HFET (VVHFET) structure which is free of dry etching damage and retains the advantage of the 2DEG. In this paper we describe a structure which uses semi-polar (11-22) GaN to achieve the crystallographic wet etching of a V-groove and channel regrowth.

2. Proposed design concept

The schematic VVHFET device structure is shown in Fig. 1. The structure is formed on a (11-22) GaN substrate which is ~58.3° from the (0001) c-plane. The V-shaped groove is obtained by a self-limiting crystallographic potassium hydroxide (KOH) wet etching. A c-plane sloping side wall is exposed on which the 2DEG is subsequently formed during regrowth. The other sloping side wall is made up of two neighbouring m-planes from the m-plane family forming a “saw tooth” profile. It should be noted that the m-plane cannot form a 2DEG as it is a non-polar plane. Detailed structural analyses will be discussed in the following sections. Instead of an inversion layer in MOS structures, a 2DEG on the c-plane side wall forms the conduction channel which allows a lower on-resistance and higher transconductance. The device operates in the same way as in an HFET where the conductance of the 2DEG channel is controlled by the gate voltage and the threshold voltage can be controlled by optimizing the composition and thickness of the AlGaN barrier. The off-state source-to-drain leakage is blocked by the p-type GaN current blocking layer (CBL). Notice that the 2DEG would be depleted if the p-type GaN is placed too close to the channel.

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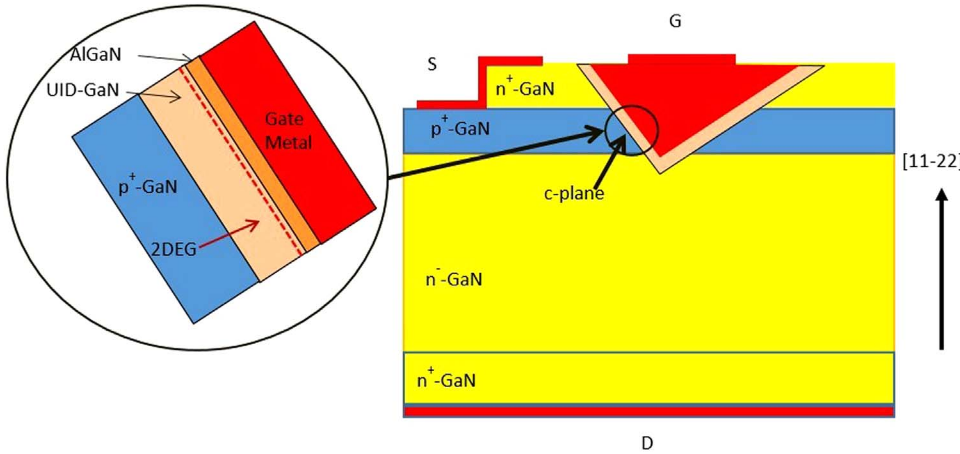

Fig. 1. Schematic structure of the proposed VVHFET on a (11-22) GaN substrate.

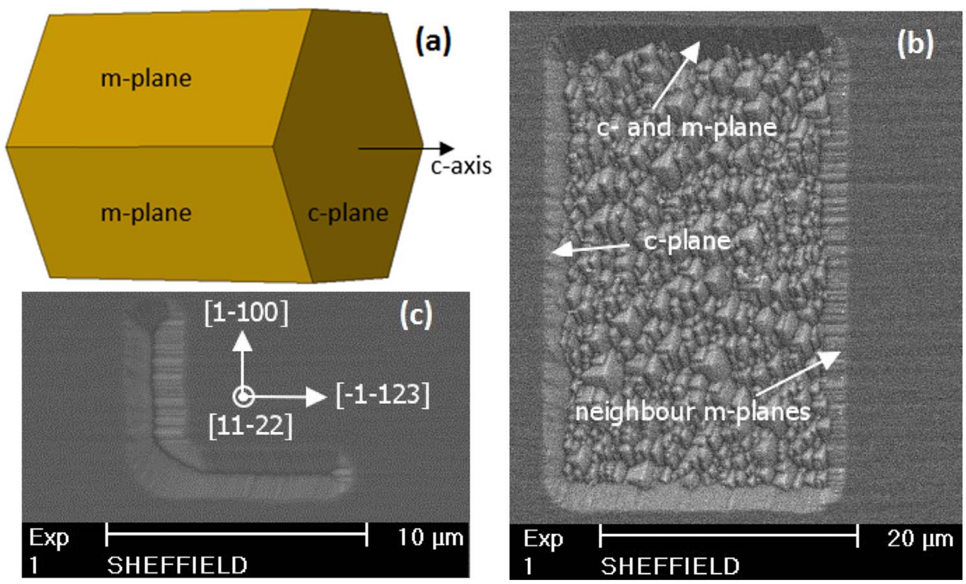

Fig. 2. (a) The schematic structure of a unit cell of wurtzite GaN oriented in [11–22] direction showing the crystallographic planes of the facets. The SEM images of the etched sample in the (b) 22 µm opening region and (c) 2 µm opening region.

Therefore, an unintentionally doped (UID) GaN channel is needed during the regrowth to separate the CBL layer and the 2DEG.

3. Sample preparation

In order to establish the etching process, a simplified structure was grown on (10-10) m-plane sapphire by metal-organic chemical vapour deposition (MOCVD). GaN grown on sapphire typically suffers from poor crystal quality due to the lattice mismatch between (11-22) GaN and m-plane sapphire substrate [13–16]. In order to improve the crystal quality, we employed an AlN interlayer technique as described in [17]. First the sample was pre-cleaned in the reactor in a H_2 ambient. Next, a pulsed nucleation layer of 25 nm GaN was grown at 800 °C, followed by a continuous growth of 700 nm GaN at 1080 °C. A 15 nm AlN interlayer was subsequently grown at 1080 °C, followed by approximately 2.3 µm of GaN. The purpose of the AlN interlayer was to act as a dislocation reduction layer, as well as a getter for unintentional oxygen incorporation on semi-polar crystals. Prior to wet etching, 100 nm SiN_x was deposited by plasma enhanced chemical vapour deposition as a hard mask. The sample was patterned by standard photolithography with the opening orientated along the [1-100] and [-1-123] axes (Fig. 2) to obtain a smooth c-plane side wall. Reactive ion etching was performed to open the windows on the SiN_x for wet etching. Subsequently, the sample was etched in 4 M KOH solution at 90 °C for 23 min with an etch rate of ~98 nm/min. Lastly, the SiN_x mask was removed by hydrofluoric acid.

In order to verify the feasibility of regrowth, the sample was degreased by standard solvent cleaning and transferred (in air) to a plasma-assisted molecular beam epitaxy (PA-MBE) chamber for re-growth. 100 nm UID GaN and 20 nm AlGaN were regrown at approximately 750 °C with an N_2 flow of 1 sccm and RF power of 200 W. The growth was under Ga-rich conditions with a Ga beam equivalent pressure of 2.1×10^{-7} Torr to ensure a smooth growth. The sample was studied by scanning electron microscopy (SEM) and transmission electron microscopy (TEM) analyses and presented in the next section.

4. Results and discussion

4.1. KOH etching of (11-22) GaN

Wet etching of (11-22) GaN has been widely investigated in light emitting diode (LED) applications and the chemical reaction mechanism and the resulting surface morphology are well understood in the literature [18–22]. Due to the negligible contribution of spontaneous polarization in semi-polar and non-polar GaN, hydroxide ions (OH^-)

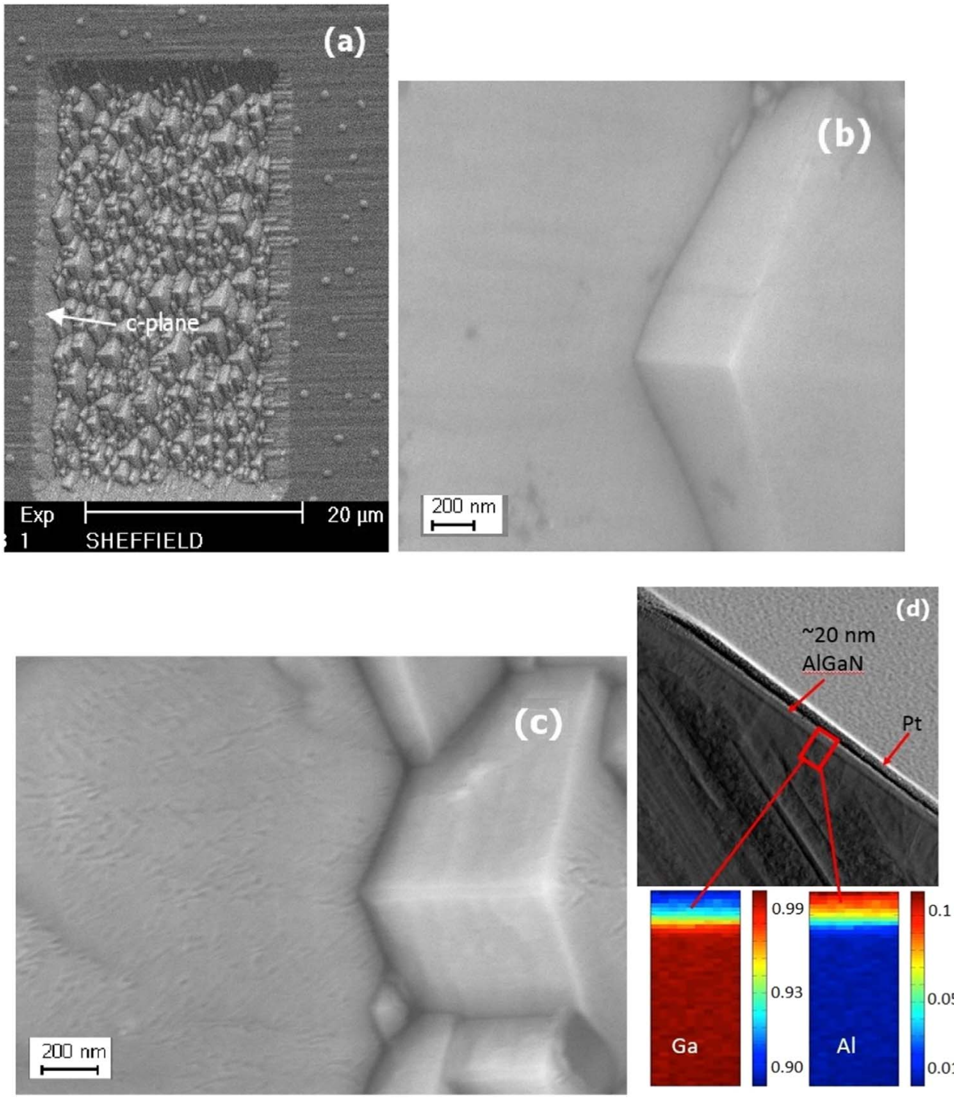

Fig. 3. (a) The SEM images of etched (11-22) GaN after MBE regrowth under Ga-rich conditions. The high resolution SEM image of the c-plane sidewall (b) before regrowth, and (c) after regrowth. (d) The cross-sectional TEM image of the regrown c-plane side wall with EDS mapping showing success growth of $Al_{0.1}Ga_{0.9}N$.

are able to access and react with surface Ga atoms following the reaction:

$$2\mathrm{GaN} + 3\mathrm{H2}O \xrightarrow[KOH]{} \mathrm{Ga2O3}+2\mathrm{NH3}$$

where the gallium oxide is subsequently dissolved in the KOH solution. However, the m-plane is more stable than the (11−22) plane due to the configuration of the atoms where more negatively charged dangling bonds of the nitrogen atoms are presenting at the m-plane surface [21,22]. In the case of c-planes the strong negative surface polarization repels the negative OH^- ions and the surfaces are almost immune to KOH.

Fig. 2(a) illustrates the top view of a unit cell of wurtzite GaN orientated in [11−22] direction. Fig. 2(b) shows the SEM images of the etched region with an opening width of 22 µm which was used to identify the crystal planes of the facets as revealed by the wet etching. Typical trigonal prism cells consisting of a c-plane and two m-plane facets from the m-plane family are observed in the central region. The crystallographic planes of the side walls can be identified from the prism-shaped features in Fig. 2(b) as well as that illustrated in Fig. 2(a). In detail, a smooth c-plane (~58.3° slope) is obtained on the left side wall. The top and bottom side walls (~62.5°) consist of c- and m-plane facets arranged in a step-like manner, whilst two m-plane facets are found on the right side wall (~31.7°).

In comparison, the etching revealed a V-groove in the L-shaped region with an opening width of ~2 µm. The side walls are in the same configuration as the 22 µm feature, but due to the reduced opening width, the (11-22) plane is fully masked by the slow etching c- and m-planes where an etch-stop is achieved. In this way, as the slopes of both side walls are fixed, the etch depth can be controlled by the opening width, which is more reliable compared to a time-based etching. However, when the sample is significantly over-etched, the resulting feature size can become larger than the as-patterned size due to a further lateral etching (most likely in the m-plane) but at a significantly reduced etch rate compared to the (11−22) plane.

4.2. MBE regrown structure

MBE was chosen for the regrowth due to its relatively low growth temperature to avoid mass transport at the high temperatures (> 1000 °C) as typically occurs in MOCVD growth [3,23]. The SEM image after the regrowth is shown in Fig. 3(a). In comparison to Fig. 2(b) (before regrowth), the formation of Ga droplets can be observed which is expected from the Ga-rich growth conditions. Figs. 3(b) and (c) present high magnification SEM images of the c-plane side wall before and after regrowth, respectively. Small pits and fissures can be observed on the c-plane surface after regrowth which are thought to be caused by the stress between AlGaN and GaN layers. Fig. 3(d) shows the cross-sectional TEM image of the c-plane side wall with energy dispersive X-ray spectroscopy (EDS) mapping showing the fraction of the Ga and Al atoms. No discernible interface is observed at the interface between underlying GaN and regrown GaN which is an indication of the good quality achieved by wet etching. A uniformly grown 20 nm AlGaN layer with a smooth interface with the underlying GaN is observed which is essential for the formation of 2DEG. The aluminium fraction of the AlGaN layer is 10% determined by EDS. We have calculated the statistical error in the measurement to be 2.7 at%. The thickness and Al fraction in the AlGaN layer are important in controlling the mount of 2DEG and hence the V_{th} of the device. It provides the opportunity for enhancement-mode operation by optimizing the regrowth conditions. Although the 10% AlGaN is somewhat lower than our expected value, it serves as a clear evidence of successful regrowth of AlGaN layer. These results are very encouraging and prove the feasibility of the design.

5. Summary

A novel design of VVHFET is proposed to achieve plasma damage-free vertical transistor structures. The device concept utilizes a semi-polar (11-22) GaN where the channel is formed on the c-plane side wall with a slope of ~58° from the (11-22) plane. A self-limiting KOH wet etching technique was developed to enable the fabrication of the device. This technique may be used in other crystal orientations to obtain c-planes at different slopes (e.g. 90° in m-/a- plane GaN), and present other interesting vertical structure possibilities such as VMOSFETs. Finally, a channel regrowth was performed by MBE. TEM analysis revealed a successful growth of $Al_{0.1}Ga_{0.9}N$ barrier with a smooth interface with the underlying GaN layer. The threshold voltage can be controlled by optimizing the barrier properties. Studies on the electrical characteristics of the 2DEG and the realisation of a complete device is underway.

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